LA-UR- R- 01-6897

Approved for public release;
distribution is unlimited.

a.\

Title: NANOSCALE PHOSPHORUS ATOM ARRAYS CREATED USING STM FOR THE FABRICATION OF A SILICON BASED QUANTUM COMPUTER

Author(s): Jeremy L. O'Brien, University of New South Wales
Steven R. Schofield, University of New South Wales
Michelle Y. Simmons, University of New South Wales
Robert G. Clark, University of New South Wales
Andrew S. Dzurak, University of New South Wales

Submitted to: SPIE International Symposium on Microelectronics & Micro-Electro-Mechanical Systems, Micro/MEMS 2001
17-19 December 2001, Adeliade, Australia

Los Alamos
NATIONAL LABORATORY

LA-UR-

Approved for public release; distribution is unlimited.

Title:

Author(s): Neil J. Curson, University of New South Wales
Bruce E. Kane, University of maryland
Neal S. McAlpine, University New South Wales
Marilyn E. Hawley, MST-08
Geoffrey W. Brown, MST-08

Submitted to:

Los Alamos
NATIONAL LABORATORY

Nanoscale phosphorus atom arrays created using STM for the fabrication of a silicon based quantum computer

J. L. O'Brien,[a,b*] S. R. Schofield,[a,b] M. Y. Simmons,[a,b] R. G. Clark,[a,b] A. S. Dzurak,[a,c] N. J. Curson,[a,b] B. E. Kane,[d] N. S. McAlpine,[b†] M. E. Hawley,[e] and G. W. Brown[e]

[a]Centre for Quantum Computer Technology, University of New South Wales, Sydney 2052, Australia

[b]School of Physics, University of New South Wales, Sydney 2052, Australia

[c]School of Electrical Engineering & Telecommunications, University of New South Wales, Sydney 2052, Australia

[d]Laboratory for Physical Sciences, University of Maryland, College Park, MD 20740, USA

[e]Los Alamos National Laboratory, Los Alamos, NM 87545, USA

ABSTRACT

Quantum computers offer the promise of formidable computational power for certain tasks. Of the various possible physical implementations of such a device, silicon based architectures are attractive for their scalability and ease of integration with existing silicon technology. These designs use either the electron or nuclear spin state of single donor atoms to store quantum information. Here we describe a strategy to fabricate an array of single phosphorus atoms in silicon for the construction of such a silicon based quantum computer. We demonstrate the controlled placement of *single* phosphorus bearing molecules on a silicon surface. This has been achieved by patterning a hydrogen mono-layer "resist" with a scanning tunneling microscope (STM) tip and exposing the patterned surface to phosphine (PH_3) molecules. We also describe preliminary studies into a process to incorporate these surface phosphorus atoms into the silicon crystal at the array sites.

Keywords: Quantum computing, nanotechnology scanning tunneling microscopy, hydrogen lithography

1. INTRODUCTION

A quantum computer relies on the laws of quantum mechanics to operate, offering massive parallelism and hence formidable computational power for particular types of problems.[1] Recent intense interest in this field has largely been fuelled by the development of algorithms demonstrated to perform classically intractable problems such as the efficient factorization of large numbers[2] and simulation of quantum systems[3] as well as rapid database searches.[4] These developments, coupled with the discovery of error correction schemes[5] designed to overcome the effects of decoherence, have propelled the start of a vigorous world-wide effort to experimentally build such a computer. A quantum computer operates on entangled states of n qubits where a qubit is a two level quantum system. To date the most advanced realisations of a quantum computer are qubit ion trap[6] and nuclear magnetic resonance[7–9] systems. However, scaling these systems to large n will be difficult,[10] making solid-state architectures,[11] with their promise of scalability, attractive. In 1998 Kane proposed a novel solid state quantum computer design[12] using phosphorus ^{31}P nuclei (nuclear spin I = 1/2) as the qubits embedded in isotopically-pure silicon ^{28}Si (I = 0). The device architecture is shown in Fig. 1 with phosphorus qubits embedded in silicon approximately 20 nm apart. This separation allows the donor electron wavefunctions to overlap, whilst an insulating barrier isolates them from the surface control A and J gates. These A and J gates control the

*Email: job@phys.unsw.edu.au

†Present address: School of Mathematical and Physical Sciences, Univ. of Newcastle, Callaghan, 2380, Australia

26. M. Copel and R. M. Tromp, "H coverage dependence of Si(001) homoepitaxy," *Phys. Rev. Lett.* **72**, pp. 1236–1239, 1994.
27. K. Hata, S. Yasuda, and H. Shigekawa, "Reinterpretation of the scanning tunneling microscopy images of Si(100)-(2×1) dimers," *Phys. Rev. B* **60**, pp. 8164–8170, 1999.
28. X. R. Qin and M. G. Lagally, "View of the empty states of the Si(100)-(2×1) surface via scanning tunneling microscopy imaging at very low biases," *Phys. Rev. B* **59**, pp. 7293–7296, 1999.
29. S. R. Schofield, J. L. O'Brien, N. J. Curson, M. Y. Simmons, R. G. Clark, G. W. Brown, and M. E. Hawley, "Electronic density of states of split-off dimers on the Si(001) surface measured by STM," *to be submitted to Phys. Rev. B* , 2001.
30. K. Oura, V. G. Lifshits, A. A. Saranin, A. V. Zotov, and M. Katayama, "Hydrogen interaction with clean and modified silicon surfaces," *Surf. Sci. Rep.* **35**, pp. 1–69, 1999.
31. A. Biedermann, E. Knoesel, Z. Hu, and T. F. Heinz, "Dissociative adsorption of H_2 on Si(100) induced by atomic H," *Phys. Rev. Lett.* **83**, pp. 1810–1813, 1999.
32. R. J. Hamers, P. Avouris, and F. Bozso, "Imaging chemical-bond formation with the scanning tunneling microscope: NH_3 dissociation on Si(001)," *Phys. Rev. Lett.* **59**, pp. 2071–2074, 1987.
33. T. C. Shen, C. Wang, G. C. Abeln, J. R. Tucker, J. W. Lyding, P. Avouris, and R. E. Walkup, "Atomic-scale desorption through electronic and vibrational excitation mechanisms," *Science* **268**, pp. 1590–1592, 1995.
34. C. Thirstrup, M. Sakurai, T. Nakayama, and M. Aono, "Atomic scale modifications of hydrogen-terminated silicon 2×1 and 3×1 (001) surfaces by scanning tunneling microscope," *Surf. Sci.* **411**, pp. 203–214, 1998.
35. C. Thirsturp private communication.
36. J. W. Lyding, G. C. Abeln, T. C. Shen, C. Wang, and J. R. Tucker, "Nanometer scale patterning and oxidation of silicon surfaces with an ultrahigh vacuum scanning tunneling microscope," *J. Vac. Sci. Tech. B* **12**, pp. 3735–3740, 1994.
37. D. P. Adams, T. M. Mayer, and B. S. Swartzentruber, "Nanometer-scale lithography on Si(001) using adsorbed H as an atomic layer resist," *J. Vac. Sci. Tech. B* **14**, pp. 1642–1649, 1996.
38. T. C. Shen, C. Wang, and J. R. Tucker, "Al nucleation on monohydride and bare Si(001) surfaces: Atomic scale patterning," *Phys. Rev. Lett.* **78**, pp. 1271–1274, 1997.
39. T. Hashizume, S. Heike, M. I. Lutwyche, S. Watanabe, and Y. Wada, "Atom structures on the Si(100) surface," *Surf. Sci.* **386**, pp. 161–165, 1997.
40. G. Palasantzas, B. Ilge, J. D. Nijs, and L. J. Geerligs, "Fabrication of Co/Si nanowires by ultrahigh-vacuum scanning tunneling microscopy on hydrogen-passivated Si(100) surfaces," *J. Appl. Phys.* **85**, pp. 1907–1910, 1999.
41. M. Sakurai, C. Thirstrup, and M. Aono, "Nanoscale growth of silver on prepatterned hydrogen-terminated Si(001) surfaces," *Phys. Rev. B* **62**, pp. 16167–16174, 2000.
42. Y. Wang, X. Chen, and R. J. Hamers, "Atomic-resolution study of overlayer formation and interfacial mixing in the interaction of phosphorus with Si(001)," *Phys. Rev. B* **50**, pp. 4534–4547, 1994.
43. N. J. Curson, S. R. Schofield, J. L. O'Brien, M. Y. Simmons, and R. G. Clark, "The interaction of PH_3 with Si(001): Adsorption and incorporation," *to be submitted to Phys. Rev. B* , 2001.
44. M. C. M. M. v. der Wielen, A. J. A. v. Roij, and H. v. Kempen, "Direct observation of friedel oscillations around incorporated Si_{Ga} dopants in GaAs by low-temperature scanning tunneling microscopy," *Phys. Rev. Lett.* **76**, pp. 1075–1078, 1996.
45. C. Domke, P. Ebert, and K. Urban, "Atomic-scale properties of the amphoteric dopant Si in GaAs(110) surfaces," *Surf. Sci.* **415**, pp. 285–298, 1998.